2 MINERνA Physics Goals and Detector Design Drivers

2.7 Generalized Parton Distributions

One of the main goals of subatomic physics is to understand the structure of hadrons, and in particular the structure of the nucleon. The primary approach to this problem has been measurement of the nucleon form-factors, with (quasi-)elastic scattering (for Q^2 up to a few (GeV/c)^2), parton densities, through inclusive deep-inelastic scattering (DIS), and distribution amplitudes, through exclusive processes. However, the usual parton densities extracted from DIS are only sensitive to the longitudinal component of the parton distributions and do not give information on the transverse component, or other contributions to the nucleon angular momentum.

2.7.1 The Nucleon Spin Puzzle and GPDs

In the late 1980's, results from polarized DIS showed that a relatively small fraction, about 20%, of the nucleon spin is carried by the valence quarks. The obvious candidates for the missing spin were the quark and gluon orbital momentum and gluon helicity. However, information on those quantities cannot be extracted from DIS.

In 1997, Ji [1, 2] showed that a new class of nucleon observables, which he called "off-forward parton distributions", could be used to determine the spin structure of the nucleon. This work, along with developments by others, especially Radyuskin [3, 4] and Collins [5] showed that these distributions, now called generalized parton distributions (GPDs), had the potential to give a full three-dimensional picture of the nucleon structure. This exciting development has led to an immense amount of theoretical work in the last few years. Short reviews can be found in [6, 7] and a comprehensive review can be found in [8].

Ji showed that in leading twist there are four GPDs, which he called H,$\tilde{H}$, E, and $\tilde{E}$, for each quark flavor. H and $\tilde{H}$ are nucleon helicity-conserving amplitudes and E and $\tilde{E}$ are helicity-flipping amplitudes. The GPDs are functions of x, ξ (a factor determining the "off-forwardness" of the reaction), and the total momentum-transfer squared, t. The GPDs can be accessed experimentally through reactions proceeding via the "handbag" diagram shown in Figure 1.

2.7.2 Deeply-virtual Compton Scattering

The most promising reaction to measure GPDs identified so far is deeply-virtual Compton scattering (DVCS). The DVCS reaction is shown in Figure 2a. An interesting feature of DVCS is that it can interfere with the Bethe-Heitler process, Figure 2b, which is completely calculable in terms of the nucleon elastic form-factors. This interference causes an asymmetry in the azimuthal distribution of the scattered proton allowing some quantities to be determined that would otherwise require a polarized target. However, DVCS involves a combination of the four GPD amplitudes, which cannot be separated using DVCS alone. Some complementary information can also be obtained from nucleon form-factor measurements and deep exclusive meson electroproduction.

Neutrino scattering provides a very similar reaction to DVCS. In this case, the virtual mediator is a $W^{\pm}$ with the production of an energetic photon, a $\mu^{\pm}$, with either a recoiling nucleon or nucleon resonance, as shown in Fig. 3. This "weak DVCS" reaction is very promising theoretically because it provides access to different GPDs than DVCS. It will help resolve the individual flavors, e.g. d in

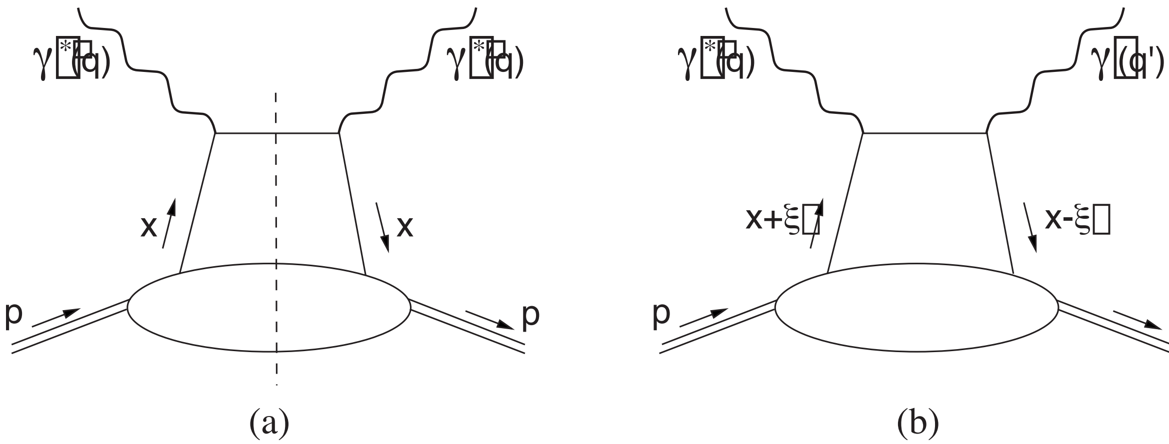

Figure 1: (a) Forward virtual Compton amplitude which describes the DIS *cross-section* via the optical theorem ($x_B = x$); (b) Handbag diagram occurring in the DVCS *amplitude*.

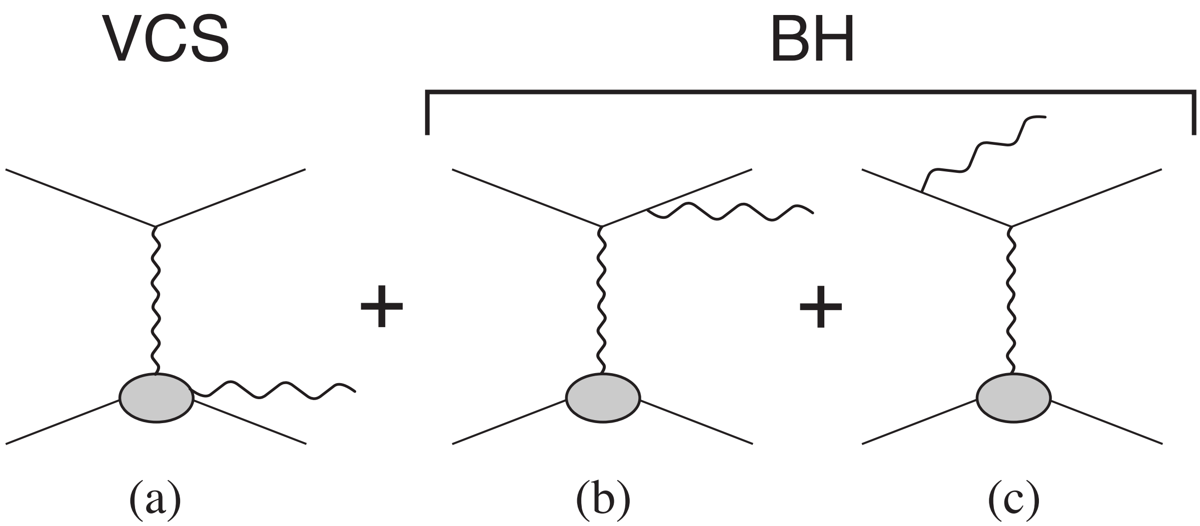

Figure 2: The DVCS process (a) along with the interfering Bethe-Heitler diagrams (b) and (c).

neutrino scattering and u in anti-neutrino scattering, and the interference of the V and A currents will give access to C-odd combinations of GPDs.

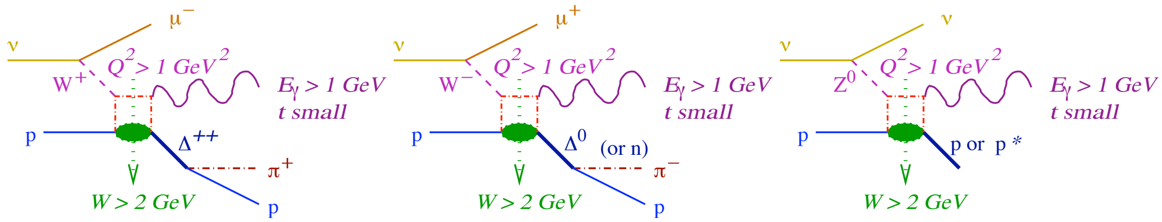

Figure 3: Reactions sensitive to GPDs in neutrino scattering.

2.7.3 Measurement of GPDs in MINERνA

Measurement of the GPDs requires measurement of exclusive processes. In addition, certain kinematic limits must be imposed to allow reliable calculations. In particular, the reaction should be above the resonance region ($W^2 > 4$ GeV^2), the momentum transfer should be small ($t < 0.2$ (GeV/c)^2), and Q^2 should be large ($Q^2 > 2$ (GeV/c)^2), which implies a high-energy photon and low-energy nucleon in the final state. Although this does present certain experimental difficulties, it should be possible to detect these for charged currents in MINERνA. A. Psaker, a student of A. Radyuskin, has made detailed calculations of the weak DVCS process for neutrinos in the 5-20 GeV range with the above kinematic constraints. He finds a cross-section of about 10^{-41} cm^2/neutron for CC reactions, with a relatively small energy dependence (the useful cross section increases slightly from 5 to 20 GeV). The cross section for protons (giving a $\Delta^{++} \to p\pi^+$ in the final state would be about half the neutron cross section. This would yield $\approx$ 10,000 events for the full four-year run with a 3 kiloton active target.

Additionally, recent work at JLab studying GPD's using DVCS have given promising results [9] for the prospects of measuring GPD's with few GeV neutrinos. The JLab results show a clear signal for GPD's measured at modest Q^2 - 1.5-2.3 GeV^2 - with a 5.75 GeV electron beam, in rough agreement with theoretical expectations. Detailed calculations for neutrino scattering are currently being done W. Melnitchouk and A. Psaker [10] which will give more precise predictions for expectations of measuring GPD's with MINERνA.

Background studies have not yet been performed, but the most significant background should be events with a photon radiated by the out-going muon. It should be pointed out that these will be primarily for reactions on neutrons in carbon, not free nucleons. We are still studying this reaction to assess the effect of extracting GPDs from a bound nucleon.

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